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On the possibility of demonstrating ionization cooling with proton beams on an internal hydrogen target in the IOTA ring at the Fermilab ASTA facility

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We propose a demonstration of the ionization cooling principle using a proton beam interacting with an internal hydrogen target in the Integrable Optics Test Accelerator (IOTA) being constructed at Fermilab in the Advanced Superconducting Test Accelerator (ASTA) facility.

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I. INTRODUCTION

Ionization cooling is a fast beam cooling process based on the interplay between the loss of momentum that a circulating beam experiences as it traverses an absorber and the reacceleration of the beam itself in radiofrequency cavities. It is best suited for muons. For electrons and positrons, multiple scattering at low energies and bremsstrahlung at high energies dominate the interaction with the absorber. For hadrons, the method is usually limited by nuclear interactions with the target.

The IOTA ring at the Fermilab ASTA facility is being designed and constructed to study nonlinear integrable optics, optical stochastic cooling, and other beam physics concepts using 150-MeV electrons. The same magnetic rigidity ($B\rho = 0.5$ Tm) would match protons of a few MeV. Because a possible candidate for an IOTA proton source is the existing HINS RFQ, we concentrate on 2.5-MeV circulating protons ($B\rho = 0.23$ Tm) interacting with a gaseous hydrogen target.

For 2.5-MeV protons, nuclear interaction cross sections are small. Longitudinally, due to the negative slope of the stopping power as a function of energy, the proton beam will be still be heated unless corrective measures are taken (such as a wedge-shaped absorber in a dispersive region or coupling with the transverse planes). Nevertheless, these experiments open up the possibility to observe for the first time transverse ionization cooling. In this note, we describe the preliminary design of such an experiment.

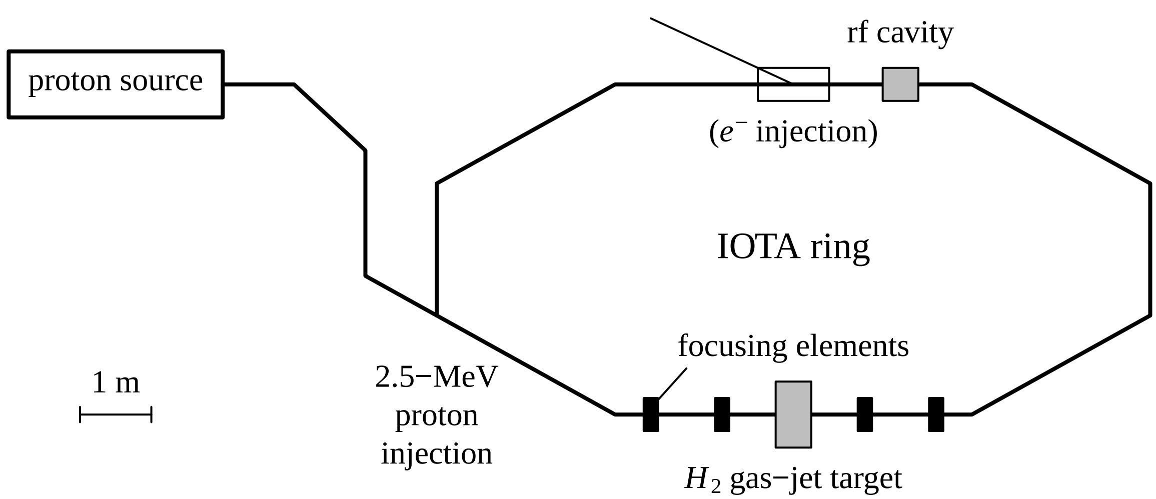

FIG. 1. Schematic layout of the apparatus.

II. DESIGN CONSIDERATIONS

A conceptual layout of the experiment is shown in Fig. 1. Protons with kinetic energy $U = 2.5$ MeV (momentum $p = 68.5$ MeV/c, velocity $\beta = 0.0729$) are injected in the IOTA ring (circumference $C = 38$ m, revolution time $T_{\text{rev}} = 1.74\ \mu$s) with an initial emittance $\varepsilon_i^n = 0.5\ \mu$m (normalized, rms) or $\varepsilon_i = 6.84\ \mu$m (geometrical, rms). Intensity is not critical for these purposes. We will consider an initial beam current $I_p = 1$ mA, corresponding to $N_p = 1.09 \cdot 10^{10}$ circulating protons. In the experimental straight section of the IOTA ring, an internal H_2 gas-jet target is installed with a thickness of $\Delta x = 5$ mm and variable density. The optics of the ring can be arranged so that the amplitude function is $\beta^* = 2$ cm in the interaction region (corresponding to an rms beam size of $\sqrt{\beta^* \cdot \varepsilon_i} = 0.37$ mm) and it does not exceed $\beta_{\max} = 10$ m around the ring ($\sqrt{\beta_{\max} \cdot \varepsilon_i} = 8.27$ mm). The minimum aperture radius in IOTA is 25 mm.

The ionization cooling rate λ_c and cooling time $\tau_c = 1/\lambda_c$ depend on the kinetic energy of the beam U, on the energy lost per turn ΔU, and on the revolution time T_{rev}. The energy lost per turn is the product of the stopping power $\langle -dE/dt \rangle$ and of the target mass thickness $\Delta t \equiv \rho \cdot \Delta x$ (ρ is the target density):

$$\lambda_c \equiv \frac{1}{\tau_c} = \frac{\Delta U}{2 \cdot U \cdot T_{\text{rev}}} = \frac{\langle -dE/dt \rangle \cdot \Delta t}{2 \cdot U \cdot T_{\text{rev}}}. \tag{1}$$

The stopping power for 2.5-MeV protons in H_2 is $\langle -dE/dt \rangle = 324$ MeV/(g/cm^2). Due to the limited momentum acceptance of the machine, the energy loss per turn $\Delta U = \langle -dE/dt \rangle \cdot \Delta t$ should be small compared to the beam energy U. We require $\Delta U/U < 1 \cdot 10^{-4}$ or $\Delta U < 0.25$ keV. This imposes a limit on the mass thickness of the target, $\Delta t < \Delta U / \langle -dE/dt \rangle = 0.77\ \mu\text{g/cm}^2 = 4.61 \times 10^{17}$ atoms/cm^2 (corresponding to a density $\rho = \Delta t/\Delta x < 1.54 \times 10^{-6}$ g/cm$^3 = 9.22 \times 10^{17}$ atoms/cm^3 and a room-temperature pressure $P = 3.77 \cdot 10^1$ mbar). With these parameters, the achievable cooling rate of transverse emittances is

$$\lambda_c = -\frac{\dot{\varepsilon}_i}{\varepsilon_i} = \frac{(0.25\ \text{keV})}{2(2.5\ \text{MeV})(1.74\ \mu\text{s})} = 2.87 \cdot 10^1\ \text{s}^{-1} = \frac{1}{3.48 \cdot 10^{-2}\ \text{s}} = \frac{1}{2 \cdot 10^4\ \text{turns}}. \tag{2}$$

Multiple Coulomb scattering of the protons on the target will tend to heat the beam. The standard deviation of the multiple-scattering angles depends on the thickness of the target in units of the radiation length $X_0 = 63.04$ g/cm^2:

$$\theta_{\text{rms}} = \sqrt{\langle \theta_{x,y}^2 \rangle} = \left(\frac{13.6\ \text{MeV}}{\beta p c} \right) \sqrt{\frac{\Delta t}{X_0}} \left[1 + 0.038 \ln \left(\frac{\Delta t}{X_0} \right) \right] = 8.25\ \mu\text{rad} \tag{3}$$

The corresponding growth rate γ_{MCS} of transverse emittances is proportional to the amplitude function in the interaction region:

$$\gamma_{\text{MCS}} = \frac{\dot{\varepsilon}_i}{\varepsilon_i} = \frac{\beta^* \cdot \theta_{\text{rms}}^2}{\varepsilon_i \cdot T_{\text{rev}}} = 1.14 \cdot 10^{-1}\ \text{s}^{-1} = \frac{1}{8.75\ \text{s}} \tag{4}$$

and it is small compared to the cooling rate.

III. COMMENTS

Because both cooling and heating rates are proportional to the target thickness, experiments should not be very sensitive to the detailed properties of the target. The required densities are out of reach for cluster jet targets, but appear to be within range for conventional ones. It may be possible to exploit the natural divergence of the jet to attempt cooling in the longitudinal plane as well (at the expense of some transverse cooling).

To mitigate the effect of multiple scattering, a low value of the amplitude lattice function is advantageous. Given the large ratio of cooling to heating rate obtained with these parameters, the amplitude function at the target does not seem to be critical. It is expected that emittance growth due to intrabeam scattering will be slow, but a more detailed study is needed to verify this assumption.

The low revolution frequency ($f_{\mathrm{rev}} = 0.57$ MHz) and beam current ($q \cdot \Delta U \cdot I_p = 0.25$ W) disfavors the use of a conventional rf cavity for acceleration. A simpler modulation circuit may be used instead. Barrier buckets may also be investigated, and whether their use would substantially change the dynamics of ionization cooling.

IV. CONCLUSIONS

This preliminary study suggests that the first demonstration of ionization cooling for particle beams could be achieved at the IOTA ring at the Fermilab ASTA facility, representing a significant addition to its accelerator physics program. Further studies are needed to establish its feasibility.

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